INTRODUCTION

One of the crucial processes in iron production is the use of the blast furnace. The blast furnace is a countercurrent chemical reactor that melts down ore and burns coke. Ascend gases reduce descending iron oxide particles through series of chemical reductions and as a result outputs pig iron [1 – 5]. Due to the coexistence of several phases and the complex flow conditions, a blast furnace is a very complex aggregate that is difficult to model and to control. Modernization of the control of the metallurgical processes is very desirable because of their high energy and material consumption. So, the blast furnace process control belongs to the key factors of their economic efficiency [6, 7].

The main purpose of the blast furnace control system is to reach specified pig iron composition, temperature and volume at the tapping. To this we need to find the optimal control data for the upper and lower part of the blast furnace (Figure 1). Difficulty of control of the blast furnace is interrelated moreover with the complexity of data acquisition from the lower zone near hearth. Control system consists mostly of a series of computer models for various phases of blast furnace operation [6, 7].

PROCESS MONITORING AND CONTROL

Monitoring and control of the blast furnace requires first of all an integrated information system with all
measured information from the blast furnace, and secondly, some appropriate on-line models. In such environment, a fully integrated on-line system for real-time monitoring of thermal state of the blast furnace lower part has been developed. This on-line system is based upon these basic components:

- Measurement, processing, archiving and visualization of the important parameters
- Models for heat generation and transfer
- Sensitivity analysis of the theoretical combustion temperature with injected fuel
- Models for heat fluxes calculation
- Isotherms and hearth wear calculation.

Fundamental for all these components are the mathematical models that consider all essential processes, and by using measured data - temperatures, hot wind parameters, etc. - calculate heat fluxes, isotherms and the theoretical temperature of the blast furnace combustion process in the area of tuyeres.

**Data measurement and processing**

For defined purposes the most important measured data are hot wind parameters, temperatures of furnace stack, belly, bosh, hearth, hearth bottom and foot plate. Measured data are sequentially:

- Tested, statistically processed and archived
- Visualized in tables or figures with temperatures values and sensors positions
- Used for heat fluxes and desired isotherms calculation and visualization.

**Models for heat generation and transfer**

As has been noted, intense heat is required as an input in the production of iron. The main part of heat is generated in the raceway zone in front of the blast tuyeres, where hot wind with powder coal, oil, oxygen, steam, etc. is piped and the coke and injected fuels are burned.

Heat generation is characterized by theoretical combustion temperature that is computed from heat balance [4, 8] and as well by composition of reduction gases. This balance includes combustion of carbon to carbon monoxide, physical heat of hot blast air. Coke and injected fuels, water vapour dissociation heat, heat of injected fuels:

\[
T_{\text{theor}} = \frac{Q_{\text{c}} + Q_{\text{v}} + Q_{\text{inj}} + Q_{\text{diss}}}{c_{\text{H}_2}V_{\text{H}_2} + c_{\text{CO}}V_{\text{CO}} + c_{\text{N}_2}V_{\text{N}_2}},
\]

where \(Q_{\text{c}}\) is the carbon combustion heat from coke and injected fuels / kJ/kg\text{coker}, \(Q_{\text{v}}\) is the physical heat of coke / kJ/kg\text{coker}, \(Q_{\text{diss}}\) is the dissociation heat of water vapour and injected fuels / kJ/kg\text{coker}, \(Q_{\text{inj}}\) is the physical heat of injected fuels / kJ/kg\text{coker}, \(V_{\text{H}_2}\), \(V_{\text{CO}}\), \(V_{\text{N}_2}\) is the volume of \(\text{H}_2\), \(\text{CO}\) and \(\text{N}_2\) in the combustion gas / m\(^3\)/kg\text{coker}, \(c_{\text{H}_2}\), \(c_{\text{CO}}\), \(c_{\text{N}_2}\) is the specific heat capacity of \(\text{H}_2\), \(\text{CO}\) and \(\text{N}_2\) / kJ/(m\(^3\)*K).

The heat transfer from the gases to walls or from the walls to cooling air or water was described with the model of radiation [9] and convective heat transfer:

\[
\sum_{j=1}^{NC} Q_{E_j} = \frac{\sum_{i=1}^{N} A_i - Q_{E_j}}{\sum_{i=1}^{N} A_i} = K_j S (T_j - T_r),
\]

where \(Q_{E_j}) = \sigma A_j T_j^4 / W\) is the radiation flux of zone \(j\), \(\sigma\) is the Stefan-Boltzmann constant, \(A_j / m^2\) is equal to \(\epsilon S\) for surface zone with area \(S\) and emissivity \(\epsilon\) and \(4V\alpha\), for volume zones with volume \(V\) and absorptivity coefficient \(\alpha\), \(K_j\) is the convective heat transfer coefficient / W/(m\(^2\)*K) and \(T_j / K\) is the temperature of the \(j\)-th zone. \(NC\) is total number of zones.

**Sensitivity analysis**

Sensitivity analysis with respect to the most important model parameters like charge composition and distribution of gas volume and temperature etc. is carried out (Figure 2).

![Figure 2. Sensitivity analysis](image)

Each input variable is examined in relation to the output variable, the theoretical combustion temperature. Sensitivity analysis gives an insight into how a change in the parameter would effect the model output. It provides the information on the significance and accuracy with which input parameters have to be estimated and controlled. The positive sign of the coefficient indicates that the input parameter "moves" in the same direction as the output parameter. The negative sign indicates movement in the opposite direction.

Figure 2 represents sensitivity analysis of theoretical combustion temperature with injected fuel. Surprising result was e.g. the big negative influence of the supplied waste oil, which was not controlled.

**Heat fluxes and isotherms calculation**

In the area of hearth, hearth bottom and foot plate the equations for heat fluxes and isotherms calculation have simplified form:
The problem of determining the thermal flux using equation (6) is now reduced to the calculation of the derivative of half order (non-integer order or fractional-order (FO)) what is not so usual. In the last decades there has been, besides the theoretical research of FO derivatives and integrals [11, 12], a growing number of applications of FO calculus in many different areas such as e.g. chaos, long electrical lines, electrochemical processes, dielectric polarization, colored noise, viscoelastic materials and of course in control theory as well [13, 14, 15] and so on.

For solving the half order derivative [10, 11, 15] in equation (6) we used for the discretizing [16] the Grunwald-Letnikov definition of the operator [12]:

$$D^q_{t_0}g(t) = \lim_{t \to q} \frac{1}{t} \sum_{j=0}^{[x]} b^q_j g(t - jr), \quad (7)$$

where \([x]\) means the integer part of \(x\), \(b^q_j\) are binomial coefficients [10, 11, 12, 15], \(r\) is time step. In order to reduce the computation cost and to eliminate the round-off error accumulation we apply the principle of "short memory", formulated in [12]. To ensure good precision in the following computation we have used the minimum "memory length" 300.

Both methods (4, 5) and (6) were implemented and compared. The first, conventional method, was used also for testing the second, unconventional method. For these purposes we have used two types of testing signals. The first was the harmonic change of the temperature at one point of the testing equipment (cooper rod). The results are depicted in Figure 3.

We can see, that the heat fluxes of both methods have the same response, the same phase shift in respect of temperature behavior. The differences are in the amplitudes, the amplitude of the second method is bigger compared to the first method. The reason is that the test-

The calculated heat fluxes are archived and so hours, workshift, and daily average values. The history of thermal load can be seen in the form of tables (Table 1) or graphs.

### Fractional-order derivatives calculation

The problem of determining the thermal flux using equation (6) is now reduced to the calculation of the derivative of half order (non-integer order or fractional-order (FO)) what is not so usual. In the last decades there has been, besides the theoretical research of FO derivatives and integrals [11, 12], a growing number of applications of FO calculus in many different areas such as e.g. chaos, long electrical lines, electrochemical processes, dielectric polarization, colored noise, viscoelastic materials and of course in control theory as well [13, 14, 15] and so on.

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The calculated heat fluxes are archived and so hours, workshift, and daily average values. The history of thermal load can be seen in the form of tables (Table 1) or graphs.
The described models and the on-line system are still in practice with significant impact for blast furnace monitoring and control. The on-line system enables to monitor directly measured temperatures, calculated theoretical combustion temperature, heat fluxes in lower and upper part of the blast furnace and isotherms that can be used for hearth and hearth bottom wear monitoring. Furthermore, plant operators can take any necessary corrective action to ensure the successful operating of the blast furnace. Minimized is the risk of thermally unsuitable situations with possibility of improving the pig iron quality and reducing the energy consumption.

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**REFERENCES**


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